

Experimental investigation of three-dimensional flow structures in annular swirling jets

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1 Introduction

Annular jet flows are of practical interest in view of their occurrence in many industrial applications in the context of bluff-body combustors [1]. They feature different complex flow characteristics despite their simple geometry: a central recirculation zone (CRZ) as a result of flow separation behind the centerbody and an outer (between the jet and the environment) and inner (between the jet and the central recirculation region) shear layer, which are both characterized by strong anisotropic turbulence [2]. The complexity of the flow is further enhanced by introducing swirl which leads to the formation of large zones of recirculation and large scale instabilities at certain swirl numbers, such as Vortex Breakdown or a Precessing Vortex Core (PVC) [3,4]. These large coherent structures have been well studied for round jets. However, in the case of annular jet flows, there is still a lot of work to do, especially regarding the interaction between the instabilities and the CRZ. The specific aim of this study is therefore to investigate the spatial and temporal characteristics of these three-dimensional flow fields by means of time-resolved Tomographic Particle Image Velocimetry measurements (Tomo-PIV). The time averaged flow field is found to be axisymmetric with a central recirculation bubble. However, looking at the transient features of the flow, a central vortex core precesses around the central axis and breaks up into a double helix when the flow becomes critical. This form of vortex breakdown is very rare and is exclusively reported in case of laminar jet flows.

2 Experimental Setup

The experiments were conducted in a water tank facility at the Aerodynamic Laboratories of Delft University of Technology. An annular jet orifice with an inner diameter $D_i = 18$ mm and an outer diameter $D_o = 27$ mm was installed at the bottom wall of the octagonal water tank (600 mm of diameter and 800 mm of height), which is made of Plexiglass to enable full optical access for illumination and tomographic imaging. The symmetry axis of the jet is aligned with the y-axis in the measurement coordinate system with the origin located at the end of the inner tube. The experiments were performed at a Reynolds number of 8,500 based on the hydraulic diameter of the annular jet ($D_h = 9$ mm). The flow in the system was driven by a pump that was submerged in a reservoir containing water mixed with seeding particles. The swirl was generated by means of a swirl generator, which consists of 12 guide vanes that can be adjusted to change the swirl strength. In this study, the swirl number based on the ratio of tangential and axial momentum times outer radius is 0.4.

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Neutrally buoyant polyamide spherical particles of 56 μm mean diameter were employed as tracer particles at a concentration of 0.65 particles/ mm^3 . The flow was illuminated by a double-pulse Nd:YLF laser (Quantronix Darwin Duo, 2×25 mJ/pulse at 1 kHz) at a wavelength of 527 nm. The light scattered by the particles was recorded by a tomographic system composed of four LaVision HighSpeedStar 6 CMOS cameras (1024×1024 pixels, 5400 frames/s, pixel pitch of 20 μm). Each camera was equipped with a Nikon 105 mm focal objective with a numerical aperture $f_\# = 32$ to allow focused imaging of the illuminated particles. The measurements were performed in a cylindrical volume with a diameter of $3.6D_h$ and a height of $5.3D_h$ at a digital resolution of 21.6 pixels/mm. The choice of a cylindrical measurement volume eliminated the need for a lens-tilt mechanism to comply with the Scheimpflug condition. Moreover, the cylindrical volume brings about a more favourable condition for the accurate reconstruction since the particle image density does not vary with the viewing angle along the azimuth and decreases when moving toward the periphery of the jet. The average particle image density is approximately 0.045 particles per pixel (ppp). The images were captured with two recording modes: (1) a double-frame mode at a low recording frequency of 50 Hz to allow a converged statistical analysis by capturing the flow for a longer period of time; a double-frame mode at a high recording frequency of 2.5 kHz to enable the visualization of the time-series phenomena.

Image pre-processing, volume calibration, self-calibration, reconstruction and three-dimensional cross-correlation-based interrogation were performed in LaVision DaVis 8.1.6. The measurement volume was calibrated by scanning a calibration target through the measurement volume. The initial calibration was refined by means of the volume self-calibration technique, resulting in a misalignment less than 0.05 pixels. The raw images were pre-processed with background intensity removal and particle intensity normalization. The particle images were then interrogated using windows of final size $48 \times 48 \times 48$ voxels with an overlap factor of 75 %, resulting in a vector spacing of 0.56 mm in each direction.

3 Results

3.1 Time averaged flow structures

To analyse the time averaged flow fields, a Reynolds decomposition was applied, dividing the velocity vector into mean and fluctuating components. Figure 1 displays the spatial distribution of the mean velocity components V and W , together with the corresponding RMS values of the fluctuating components in a (xy) cross sectional plane of the measurement volume. In this plane, V is the axial and W the tangential velocity component. All quantities are scaled with respect to the mean axial velocity of the jet, U_o . The flow field is axisymmetric and hence a planar representation is sufficient to reveal the flow structures. As shown in Figure 1a, the axial velocity distribution reveals two large regions of backflow. The first region is the CRZ behind the central tube. The swirl induces a radial pressure gradient to balance the centrifugal forces, according to:

$$\frac{\partial p}{\partial r} = \rho \frac{W^2}{r}, \quad (1)$$

where r is the radial direction. These swirl-induced pressure gradients open the CRZ and create a toroidal vortex, as also found in the study by Vanierschot et al. [3]. Downstream of this vortex, the tangential velocity is high near the central axis due to the conservation of angular momentum as shown in Figure 1b. The increased tangential velocity make the flow critical and leads to Vortex Breakdown [4]. Judged on the time averaged axial velocity representation in Figure 1a, Vortex Breakdown occurs at $y/D_o \approx 0.8$. As Figures 1c and 1d confirm, this region is characterized by intensive mixing and highly anisotropic Reynolds stresses.

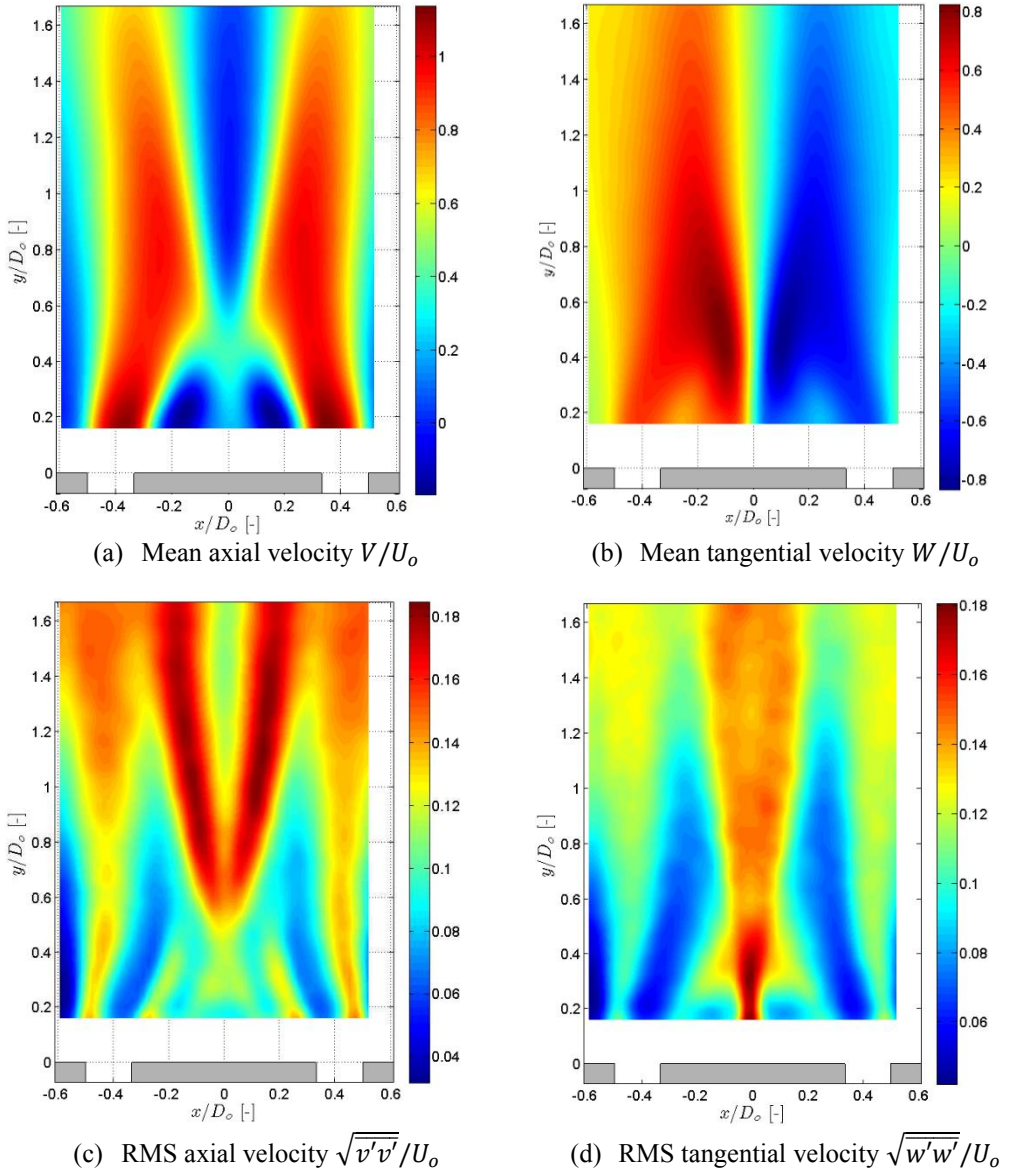


Fig. 1. Mean and RMS values of the axial and tangential velocity components.

3.2 Instantaneous flow structures

The instantaneous flow field of the jet is shown in Figure 2a. The black isosurfaces are contours of zero axial velocity and the transparent contours are isosurfaces of Q and hence represent the vortical structures. Two distinct structures can be observed. The first one is the CRZ behind the centerbody. As can be seen in the time averaged flow in Figure 2b, the CRZ is a toroidal vortex as the isosurface of Q is a ring. The second flow structure is the Vortex Breakdown bubble further downstream of the CRZ. This bubble is an elongated zone of recirculation which is highly turbulent (see Figures 1c and 1d). As the Q criterion reveals in Figure 2a, the central vortex core at the central axis “breaks up” into a double helix, which is wrapped around the recirculation bubble. This double helix precesses around

the central axis, which is known as the precessing vortex core [4]. To the authors' knowledge, this double helix structure has not been revealed previously for annular jet flow.

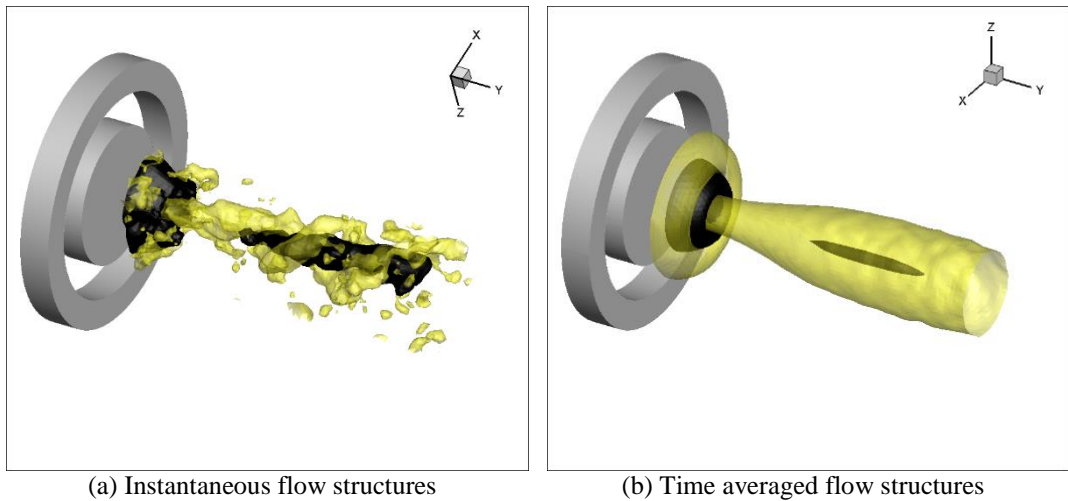


Fig. 2. Instantaneous and time averaged flow structures of the jet.

4 Conclusions

In this study, the instantaneous and time averaged flow structures of an annular swirling jet flow have been studied using time-resolved Tomographic Particle Image Velocimetry (TOMO-PIV) measurements. Two distinct flow structures were identified. The first one is a toroidal central recirculation zone behind the centerbody. This torus is created by a swirl induced pressure field to balance the centrifugal forces. Further downstream, the conservation of tangential momentum creates regions of high tangential velocities. This promotes vortex breakdown, which is the second large scale flow structure in the flow field. The visualization of the instantaneous flow reveals that the central vortex core breaks up into a double helix, which is wrapped around the breakdown bubble. To the authors' knowledge, no previous studies on annular jet flow have revealed this interaction.

References

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